Hybrid Mathematical Model of Wind Turbine for Assessment of Wind Generation Impact on Transients in Power Systems

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Abstract

Nowadays in the world a lot of attention is paid to the integration of renewable energy sources, especially wind power plants, into existing electric power systems. However, the modern simulation tools usage based on numerical integration for studying and assessment of renewables impact on transient processes in EPS is always associated with different simplifications and limitations. In this regard, the authors suggest the Hybrid Real-Time Power System Simulator (HRTSim) usage for comprehensive and accurate simulation of large-scale EPS with RES. The results of the synthesis of the wind turbine mathematical model as a part of the specialized module for the HRTSim are presented in the paper. The developed means are intended to solve the issue of this hardware-software simulator upgrade for comprehensive and adequate modelling of wind power generation facilities.

Keywords: Wind turbine, Mathematical modelling, Hybrid simulation, Pitch control, Electric power system.

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1. Introduction

Electricity consumption in the world is rapidly increasing and over the last 15 years it has amounted to approximately 35-40 %. This trend leads to the need of new power generation capacities. In most developed countries for obvious reasons (ensuring energy and environmental safety, etc.) the renewable energy sources (RES) are preferred. The total generation capacities of RES is approximately 2195 GW that is about 26.5 % of world generation [1]. Statistic shows that the power capacities obtained from the use of RES has more than doubled from 2007 to 2017. Overall, 70 % of the capacities increase in the world comes from renewables in 2017. The leading positions in the area of electric power engineering among RES are occupied by wind turbines (WT) united in wind power plants (WPP), the total generation capacities of which at the end of 2017 were about 539 GW.

In Russia, the RESs integration is one of the most discussed topics in the area of power engineering. In particular, it is planned to build WPPs in different regions with a total power of 1.5 GW [2].

However, the integration of a large amount of RESs, especially on the basis of wind power generation (WPG), into existing EPSs significantly changes the structure of generating capacities, leads to problems of EPS regime and emergency control, issues of unevenness and difficult prediction of RES operation, the need to assess their impact on regimes and processes in EPS. Moreover, WPG has a significant impact on the operation of relay protection and automation (RPA) of a nearby power district [3]. In addition to the direct impact on the RPA devices, WPG integration due to the growth in the use of power electronics in EPS (the main capacity additions is due to Type-III and Type-IV WTs [4] connected to the network via power converters) poses new challenges [5], [6]. One of the most serious problems associated with the large-scale integration of such facilities is the reduction of the power system inertia, which also becomes time-varying due to the continuous change in WTs generated power. The EPSs with less inertia are less stable in cases of serious accidents [7], [8].

Therefore, the comprehensive and reliable information about the processes in the equipment, WPPs and EPS as a whole in case of various normal and abnormal modes of their operation is necessary to solve the indicated issues. Modern EPSs with RESs are complex technical dynamic systems in which all equipment is continuously interconnected by a single continuous spectrum of quasi-steady-state and transient processes. Thus, the study of the aggregate mathematical model of any EPS with RES via numerous software and hardware-software power system simulators (SPSS and HSPSS, respectively) based on strictly numerical integration methods, is carried out taking into account very significant simplifications and limitations [9]. As a result, there is an urgent need to use an alternative simulation tool, relative to the existing SPSS and HSPSS, which allows to solve the issues of adequate modelling of EPS with RES.

The practical implementation of such tool is a multiprocessor software and hardware system – Hybrid Real-Time Power System Simulator (HRTSim), based on the EPS hybrid simulation concept [10], [11]. On the basis of this simulator, the most effective methods and modelling means for all types of WPG are being developed.

2. Components of Wind Turbine Hybrid Mathematical Model

In general, the model of any WPG installation can be divided into two parts: mechanical part (wind model, turbine model) and electrical part (generator model, power converter model). The focus of this article is on the principles of WT mathematical model implementation in the specialized hybrid processor of WT (SHP WT) for HRTSim schematic structure is shown in Figure 1.

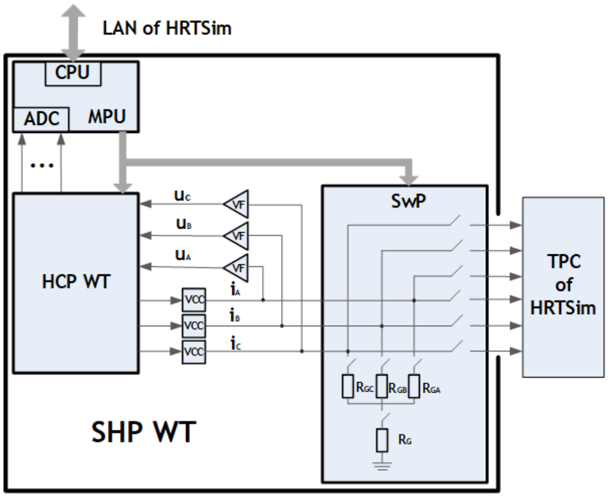

Figure 1. SHP WT schematic structure: *LAN - local area* network; CPU – central processing unit; ADC – analogue-to-digital convertor; MPU – microprocessor unit; HCP WT – hybrid coprocessor of WT; VCC – voltage-current converter; VF – voltage follower; SwP – switching processor; TPC – three-phase commutator cross-board; RG, RGA, RGB, RGC – ground fault resistance; Ua, Ub, Uc - voltage; ia, ib, ic - current

In addition, the results of its testing are also presented in the paper.

2.1. Wind Model

With regard to the applied challenge of WTs simulation, taking into account the results of scientific works of many scientists [12, 13], the wind model is represented as a sum of two components:

$$V_{wind}(t) = V_{wind,mean} + dV(t) \quad (1)$$

where $V_{wind,mean}$ is a systematic (slowly changing) component (mean wind speed); dV(t) is a dynamic (rapidly changing) component (turbulence component).

The spectral method is commonly used in wind energy engineering to determine the dynamic component (turbulence). Turbulence has random nature and can be described by random functions of one or more variables. The method of spectrum analysis (harmonic transform) is applied to the functions of random processes. In harmonic analysis, the most convenient description is the Fourier series, evaluated in a complex form (functions $e^{i\omega t}$). Therefore, the function $V_{wind}(t)$ can be described by the equation (2):

$$V_{wind}(t) = V_{wind,mean} + \sum_{i=0}^{N} A_i \cos(\omega_i t + \varphi_i) \quad (2)$$

where φ_i is a phase of each harmonic, which is randomly generated, with a uniform distribution in the domain [π; -π].

The total value of each wind *i*-component is determined by the corresponding value of the power spectral density $S(\omega_i)$, where ω_i is the discrete angular frequency.

Today, the most widely used spectral densities in world practice for the turbulence component of the wind model are von Karman, Kaimal and Davenport wind speed power spectrums [14]. Kaimal spectrum is adopted for further implementation (3):

$$S(\omega_i) = \frac{\frac{2}{3}\sigma^2 \cdot \frac{L}{V_{wind,mean}}}{\left(1+\frac{\omega_i}{2\pi}\cdot\frac{L}{V_{wind,mean}}\right)^{\frac{5}{3}}} \quad (3)$$

where σ is the turbulence intensity; *L* is the turbulence length scale.

As can be seen from the equation (3), it is also necessary to determine the values of σ and *L* to calculate the spectral density of turbulence, according to Kaimal spectrum. The parameters for the wind dynamic component calculation are taken according to [14]. The longitudinal scale parameter of the wind flow turbulence Λ at the height of the WT hub *H* is expressed by the formula (4):

$$\Lambda = \begin{cases} 0.7 \cdot H & H \le 60\,m \\ 42\,m & H > 60\,m \end{cases} \quad (4)$$

Then, to calculate the turbulence length scale L, the expression (5) is used:

$$L = 8.1 \cdot \Lambda \quad (5)$$

The turbulence intensity σ at the height of the WT hub and for standard types of WTs are given by (6):

$$\sigma = 0.12 \cdot (0.75 \cdot V_{wind,mean} + 5.6) \quad (6)$$

Thus, the harmonic at frequency ω_i has an amplitude A_i (7):

$$A_i = \frac{2}{\pi}\sqrt{\frac{1}{2}[S(\omega_i) + S(\omega_{i+1})] \cdot [\omega_{i+1} - \omega_i]} \quad (7)$$

2.2. Turbine Model

It is principally needed to calculate the mechanical torque of the turbine at various wind speeds for the adequate WT simulation. Detailed mathematical expressions describing the WT mechanical torque were developed by N.E. Zhukovsky, G.H. Sabinin, G.F. Proskura, Krasovsky, E.M. Fateev [15], [16]. However, these expressions are attached to the real geometry of the WT and take into account their braking coefficient, blade camber, tip loss factor, etc. Due to the impossibility of obtaining field data for specific WT types, a WT mathematical model was proposed that calculates the power and torque via the power coefficient of the rotor [17], [18]. Thus, the actual mechanical power produced by the WT can be determined from the equation (8):

$$P_{WT} = \frac{1}{2}\rho\pi R^2 C_P(Z,\beta) V_{wind}^3 \quad (8)$$

where: ρ - air density [kg/m^3]; R - WT radius [m]; $C_P(Z, \beta)$ - power coefficient (Betz limit); Z - WT tip speed ratio; β - blade pitch angle [*deg*].

The power coefficient C_P in the equation (8) is the fraction of the energy transmitted to WT by the wind flow and characterizes the WT efficient use of wind energy passing through the area swept by the WT. Consequently, it is necessary to know the power coefficient for appropriate calculation of the energy produced by WT at a specific wind speed. The power coefficient is a non-linear function whose value is unique to each turbine type. The C_P curves usually determined experimentally and provided by the WT manufacturers. The $C_P(\beta, Z)$ function is also necessary if the pitch angle control is implemented in the WT model, which is normative for modern types of WTs.

There are two main ways to determine $C_P(\beta, Z)$ in the presence of initial experimental data. The first method is the tabular input of the C_P curves and, if there is enough data, linear interpolation (or quadratic derivation) can be used to obtain intermediate power coefficient values. However, this method requires the input of a significant amount of data - at least 15 points per curve and at least 20 C_P curves at different angles β.

The second method is the approximation of the $C_P(\beta, Z)$ by an analytic nonlinear function. According to [17], the C_P curves for a WT can be described, for example, using expression (9):

$$C_P(Z,\beta) = C_1\left(\frac{C_2}{Z_i} - C_3\beta - C_4\beta^{C_5} - C_6\right)e^{-\frac{C_7}{Z_i}} \tag{9}$$

where

$$Z_i = \frac{(\beta^3+1)(Z+C_8\beta)}{(\beta^3+1)+[C_9(Z+C_8\beta)]} \tag{10}$$

It can be used the multidimensional optimization method to find the coefficients C_1-C_9. As a result, the approximate coefficients for different types of WTs are presented in Table 1.

Table 1. Coefficients for the C_P curves of WT

WT types	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Type-I and Type-II	0.44	125	0	0	0	6.94	16.5	0	-0.002
Type-III and Type-IV	0.73	151	0.58	0.002	2.14	13.2	18.4	-0.02	-0.003

Thus, the WT mathematical model schematic structure is shown in Figure 2.

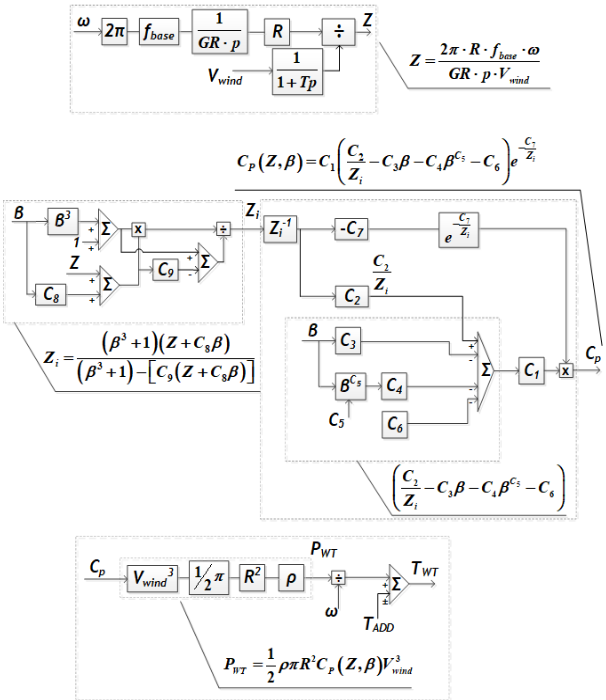

Figure 2. Schematic structure of the WT mathematical model: *GR - gear ratio; p - electric machine pole pairs; T_{ADD} - additional mechanical torque for different tests; T_{WT} - resulting mechanical torque of WT; f_{base} - network frequency*

2.3. Pitch Control Model

A major part of the WT is monitoring and control system that provides mechanical part control (pitch angle control) and electrical part control (power converter control, rotor torque control). The control system consists of equipment for the blades angle control, the yaw position control and the generation operation. The system also includes monitoring and measurement equipment necessary for determination of wind speed, temperature, pressure, torque, electric power and other data, that are important for the normal operation of WTs, and the transmission of these data to the control centre, remoted from the WTs. The control system also consists of the equipment necessary to control the WT during its maintenance.

According to the method of power control via blades angle changing, all wind turbines are divided into two types [17]: WT with *pitch control* and *stall control*. *Pitch control* is the blade pitch angle changing in accordance with the wind speed; *stall control* implies that the blade angle is unchanged, but the blade profile is such that the efficiency of individual blade sections decreases with increasing wind speed. As a result, the WT power generation growth does not occur or occurs, but not significantly, after reaching the rated power and further increasing in the wind speed.

Stall control is commonly used in the fixed-speed WT (Type-I and Type-II) [19], [20] or in turbines of about 1 MW and less. Stall control is based on a specific position of wind turbine blades that attaches to the hub at a fixed angle. A blade aerodynamics is designed in such a way that as the wind speed increases, the shape of the blade gradually begins to create turbulence and, consequently, as a result leads to a slower speed of the blades, due to disruption of the wind flow. The advantage of this design is that it avoids mechanical moving parts, control systems and other difficulties associated with the pitch control.

Wind gusts lead to abrupt changes of turbine torque and, accordingly, generator power. As a result, strong gusts require a more robust construction for a mechanical drive-train system. In addition, if such WTs are used in EPS with a low stability level, they can lead to significant voltage fluctuations.

Active stall control is used in more powerful Type-I and Type-II WT (>1 MW) [21]. In such systems in addition with stall control, the WTs have a mechanism for the pitch angle control. Despite the fact that the WTs have a fixed speed, the blade angle changing at low wind speeds allows to change C_P and, consequently, increase the efficiency of WTs. In case of high wind speeds, when the WT has reached its rated power, active stall control allows to control the WT much better than in case of conventional stall control. If the wind speed suddenly increases, the active stall control system changes the WT blades angle in order to boost rotation speed reduction.

Pitch control (blade pitch angle changing relative to its axis) is used in variable-speed WTs (Type-III and Type-IV). Pitch control at different wind speeds allows to maintain WT power close to the rated. There are three main zones of the pitch control system [19]-[21]:

Zone 1: includes modes of WT inactivity and starting. The regulation strategy in this zone is to track wind speed. In the case of a cut-in wind speed, the operations required to start the machine begin.

Zone 2: is the operation mode, the task of the control system is to generate maximum power. In zone 2, two principles of the WT control can be used: hub rotation in the horizontal axis and mechanical torque changing. The aim in this zone is to maintain the maximum C_P of WT.

Zone 3: Pitch control system of WT should limit the C_P in order not to go beyond the limits of the WT electrical and mechanical loads. In zone 3, Type-III and Type-IV WTs maintain the constant value of rotation speed and the rated power via pitch angle changing. All three of the above-mentioned principles of power generation control can be used in zone 3.

The pitch angle value depends on the WT datasheet or on the $C_P(Z, \beta)$ curves. The pitch angle control system is a servo drive with specified control algorithms. The control systems based on the rotor rotational speed control (Type-III WT) or the power generation control (Type-IV WT) are mainly used [19].

Detailed models of WT control systems are given in [20, 21]. Control systems are mainly implemented on proportional-integral (PI) and proportional-integral-derivative (PID) algorithms. The PI controllers are generally used in WTs. The PI-based control systems have a smoother transient process compared to the PID algorithm. The presence of noises in the measurement channel of PID controller leads to significant random fluctuations in the control signal, which increase the variance of the regulation error.

According to the analysis of currently used pitch controllers, the model consist of all the necessary elements for the correct operation of pitch angle control is presented in Figure 3.

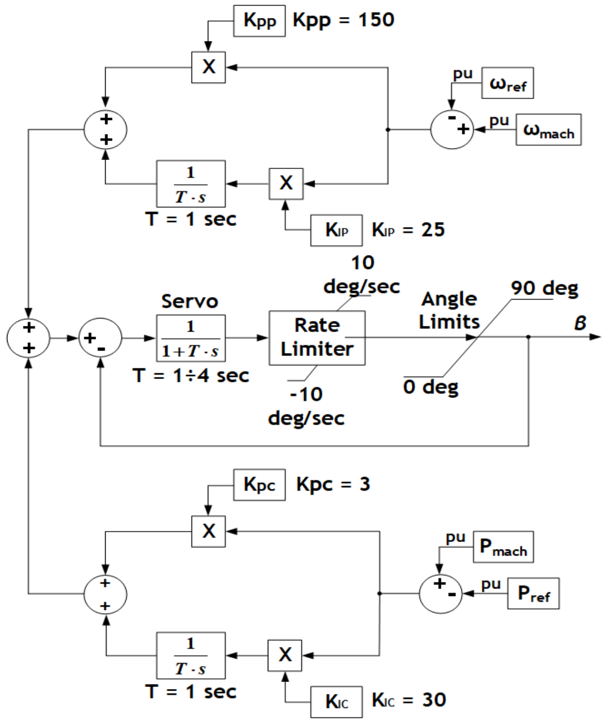

Figure 3. Schematic structure of pitch control model: K_{PP} - proportional frequency coefficient; K_{IP} - integral frequency coefficient; ω_{ref} - WT shaft rated speed; ω_{mach} - current WT shaft speed; Servo - servomotor; K_{PC} - proportional active power coefficient; K_{IC} - integral active power coefficient; P_{ref} - WT rated active power; P_{mach} - current WT active power

The implementation of the WT mathematical model and its control system was performed in the MPU block of the SHP WT (Figure 1) on the basis of ARM-based AT91SAM7X256 microcontroller.

3. Results and Discussion

3.1. Wind Turbine Model Tests

The following are the experimental studies to assess the adequacy of the implementation and operation of the WT mathematical model. In the study of any WT models, there are two main modes of its operation – at different wind speeds and at different pitch angles. Based on these modes, WT power characteristics are plotted, from which can be qualitatively assessed the correctness of the implemented WT model operation. In this regard, the main power characteristics of WT ($P_{WT} = f(V_{wind})$; $C_P = f(Z)$), experimentally obtained via developed program code for MPU of SHP WT, were compared with similar data, obtained by PSCAD simulation software according to Figure 2 and Figure 3, in two cases:

– *Case 1*: different pitch angles $\beta = 0°, 2° \dots 25°$ and constant wind speed V_{wind} = 10,8 m/s - $C_P = f(Z)$ curves (Figure 4);

– *Case 2*: different pitch angles β = 0°, 2° … 25° and different wind speed V_{wind} = 0 … 25 m/s – $P_{WT} = f\ (V_{wind})$ curves (Figure 5).

According to Figures 4 and 5, the WT power characteristics obtained experimentally via SHP WT coincide with the theoretical characteristics.

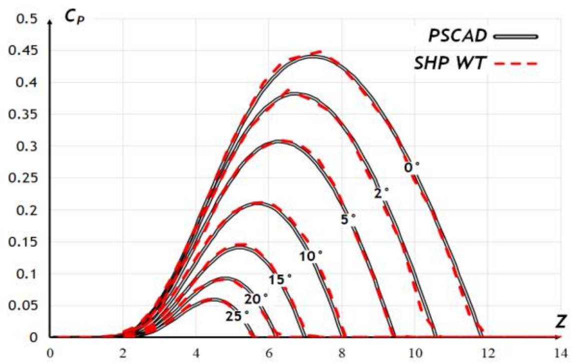

Figure 4. $C_P = f\ (Z)$ curves for *Case 1*

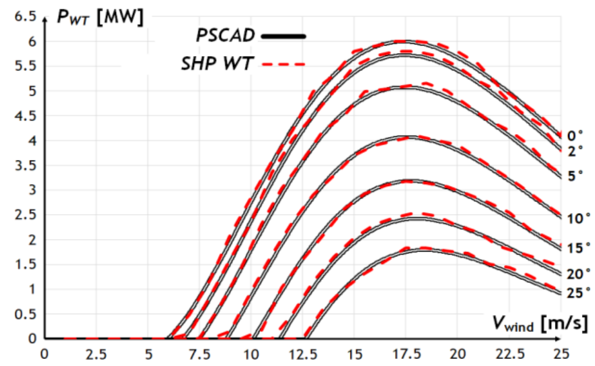

Figure 5. $P_{WT} = f\ (V_{wind})$ curves for *Case 2*

This fact indicates the adequacy of the operation of the synthesized WT mathematical model. Moreover, the obtained characteristics provide an opportunity to assess the operation of the WT aggregate model with specific parameters (radius, generator rated power, etc.) in case of various wind speeds and pitch angles.

In addition, the values of the WT main parameters for various initial data, obtained during experimental studies of SHP WT, are given in Table 2.

Table 2. Comparison of SHP WT and PSCAD data (WT model tests)

WT parameter	Number of initial parameters					
	1			2		
	SHP WT	PSCAD	Error, %	SHP WT	PSCAD	Error, %
ω_{mach} [rad/s]	1.375	1.374	0.073	1.310	1.309	0.076
Z	6.873	6.872	0.015	7.202	7.205	0.049
Z_i	6.757	6.733	0.356	7.068	7.053	0.213
β [deg]	0.0	0.0	0.000	0.0	0.0	0.000
C_P	0.441	0.438	0.685	0.439	0.441	0.499
P_{WT} [MW]	5.287	5.252	0.666	3.941	3.964	0.580
T_{WT}	0.501	0.500	0.200	0.393	0.396	0.758

The obtained data was compared with the values obtained using PSCAD software. The maximum error is achieved only in the modes when the WT generated power approaches zero. In operating modes of a WT at rated parameters, the error of the obtained values does not exceed 5%.

3.2. *Pitch Control Model Tests*

In the next stage, experimental studies of the WT aggregate model were carried out, taking into account the pitch control, implemented in the SHP WT for HRTSim, according to the following scenario:

– Testing of the adequate operation of the WT pitch control in case of steps in wind speed of 1 m/s;
– Testing of the adequate operation of the WT pitch control, taking into account the wind dynamic model, implemented according to the Kaimal spectrum (reproducing of the wind turbulence in a time frame).

Based on the analysis of the obtained data, the controller parameters (gains) can be refined and optimized. A similar approach is needed to test the model under various operating conditions. The resulting oscillograms of the operation of the pitch control, obtained via SHP WT and PSCAD, are presented in Figures 6 and 7.

Figure 6 shows the resulting oscillograms of pitch control system operation as part of the aggregate WT model (including WT and generator), as well as the standard WT parameters such as pitch angle, generator rotation speed and generated active power at various wind speeds (the rated wind turbine power is 5 MVA, the reference – 3.5 MW).

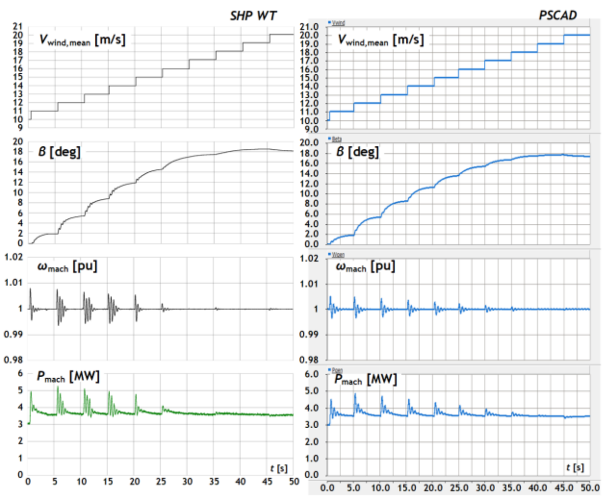

Figure 6. Resulting oscillograms of the operation of the WT pitch control in case of steps in wind speed (from 10 m/s up to 20 m/s)

In the case of low wind speeds, less than the rated value of 10.8 m/s, the pitch control is inactive, and the pitch angle is maintained equal to the optimal value – zero. At the same time, power generation begins only at wind speeds greater than 6 m/s. The observed power surges and oscillations are associated with steps in wind speed and, therefore, steps in the WT power (mechanical torque).

Based on Figure 6, it can be seen that the pitch control model operates correctly: (1) with excess wind energy (with an increase in the wind speed), the wind turbine begins to produce an excess amount of active power compared to the reference value; (2) therefore, the pitch angle begins to increase in order to reduce the resulting amount of power generation, thereby reducing the generation of WT active power to the reference value; (3) with a decrease in the wind speed, the WT begins to produce less active power, and, therefore, the control system reduces the pitch angle to a minimum value in order to maximize the amount of power generation.

Figure 7 presents the resulting oscillograms of the wind dynamic models and pitch control system as a part of the aggregate WT model in a time frame of 100 seconds.

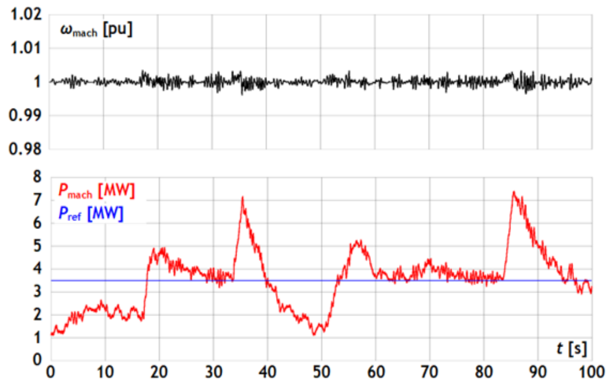

Figure 7. Resulting oscillograms of the operation of the WT pitch control in case of wind dynamic model

The rated and reference power of the WT are set similarly to the previous experiments. According to the obtained oscillograms, it can be concluded that the wind model and the pitch control model operate adequately - the same logic can be traced as in the experiments given above.

In addition, the values of the WT main parameters for various wind speeds are given in Table 3.

Table 3. Comparison of SHP WT and PSCAD data (pitch control model tests)

WT parameter	1			2			3		
	SHP WT	PSCAD	Error, %	SHP WT	PSCAD	Error, %	SHP WT	PSCAD	Error, %
V_{wind} [m/s]	11.000	11.000	0.000	15.800	15.800	0.000	23.300	23.300	0.000
β [deg]	1.885	1.855	1.645	16.065	15.104	6.363	14.089	13.394	5.186
Z_i	6.775	6.704	1.054	4.379	4.404	0.569	2.905	2.923	0.629
Z	6.763	6.760	0.048	4.700	4.706	0.131	3.186	3.191	0.166
C_P	0.388	0.387	0.351	0.128	0.130	1.895	0.041	0.041	0.784
P_{WT} [MW]	3.579	3.571	0.232	3.492	3.571	2.205	3.573	3.570	0.070
T_{WT}	0.715	0.714	0.120	0.697	0.714	2.401	0.715	0.714	0.126
ω_{WT} [rad/s]	1.240	1.239	0.057	1.240	1.239	0.057	1.240	1.239	0.057

Based on this table, it can be seen that the error exceeds 3%, only for cases of increased wind load.

4. Conclusion

At present, the research team continues to develop universal SHP of WT that can reproduce any existing type of WT (including doubly-fed induction generators, permanent magnet generators, power converters, etc.). The implementation of such models in the HRTSim will provide both the opportunity for a detailed study of WTs and WPPs, and the opportunity for a comprehensive study of the impact of their integration into existing EPS. In addition, the HRTSim usage for detailed and adequate modelling of large-scale EPS with the RES for further study of various modes and fault disturbances allows to solve a number of urgent issues, such as: (1) study of the impact of the processes spectrum in EPS with a significant share of RES on the operation of the RPA; (2) assessment of the possibility of RES participation in the regulation of voltage and reactive power, the regulation of frequency and active power, their operation in the zone of low or high frequency and voltage levels, adopted in EPS, without generation facilities disconnection from the network by automation within a certain time interval, etc.

5. Bibliographic References

[1] *Renewables 2018 Global Status Report*, viewed on 24 april 2019, retrieved form: http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_-1.pdf

[2] *ROSNANO*, viewed on 25 april 2019, retrieved form: http://www.rusnano.com/about/press-centre/news/20180613-rosnano-fond-razvitiya-vetroenergetiki-poluchil-pravo-stroitelstva-823-mvt-vetrogeneratsii

[3] TELUKUNTA, V., PRADHAN, J., “Protection challenges under bulk penetration of renewable energy resources in power systems: A review”, *CSEE Journal of Power and Energy Systems*, 2017, vol. 3, no. 4, pp. 365-379, ISSN 2096-0042.

[4] MULJADI, E., ZHANG, Y., GEVORGIAN, V., KOSTEREV, D., “Understanding dynamic model validation of a wind turbine generator and a wind power plant”, in: Proceedings of the 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, USA, 2016, pp. 1-5.

[5] WU, Q., SUN, Y., *Modelling and Modern Control of Wind Power*, 1st ed., New Jersey: Wiley-IEEE Press, 2017.

[6] REKIOUA, D., *Wind Power Electric Systems*, 1st ed., New York: Springer, 2014.

[7] XIE, L., CARVALHO, P.M.S., FERREIRA, L.A.F.M., LIU, J., KROGH, B.H., POPLI, N., ILIC, M.D., “Wind Integration in Power Systems: Operational Challenges and Possible Solutions”, *Proceedings of the IEEE*, 2011, vol. 99, no. 1, pp. 214-232, ISSN 1558-2256.

[8] EFTEKHARNEJAD, S., VITTAL, V., HEYDT, G.T., KEEL, B., LOEHR, J., “Impact of Increased Penetration of

Photovoltaic Generation on Power Systems", *IEEE Transactions on Power Systems*, 2013, vol. 28, no. 2, pp. 893-901, ISSN 1558-0679.

[9] SUVOROV, A., GUSEV, A., RUBAN, N., ANDREEV, M., ASKAROV, A., STAVITSKY, S., "The Hybrid Real-Time Dispatcher Training Simulator: Basic Approach, Software-Hardware Structure and Case Study", *International Journal of Emerging Electric Power Systems*, 2019, vol. 20, no. 1, pp. 1-15, ISSN 1553-779X.

[10] ANDREEV, M.V., GUSEV, A.S., RUBAN, N.Y., SUVOROV, A.A., UFA, R.A., ASKAROV, A.B., BEMS, J., KRALIK, T., "Hybrid Real-Time Simulator of Large-Scale Power Systems", *IEEE Transactions on Power Systems*, 2019, vol. 34, no. 2, pp. 1404–1415, ISSN 1558-0679.

[11] ANDREEV, M., BOROVIKOV, Y., GUSEV, A., SULAYMANOV, A., RUBAN, N., SUVOROV, A., UFA, R., BEMS, J., KRALIK, T., "Application of Hybrid Real-time Power System Simulator for Research and Setting a Momentary and Sustained Fast Turbine Valving Control", *IET Generation, Transmission and Distribution*, 2018, vol. 12, no. 1, pp. 133–141, ISSN 1751-8695.

[12] ANAYA-LARA, O., JENKINS, N., EKANAYAKE, J., CARTWRIGHT, P., HUGHES, M., *Wind Energy Generation Modelling and Control*, 1st ed., Chichester: John Wiley & Sons, 2009.

[13] CHAKRABARTI, S., *Handbook of Offshore Engineering*, 1st ed., London: Elsevier Science, 2005.

[14] IEC 61400-1: 2019, *Wind energy generation systems – Part 1: Design requirements*.

[15] KRASOVSKY, N.V., SABININ, G.H., *Problems of wind energy use*, Moscow, 1923.

[16] ZHUKOVSKY, N.E., *Vortex propeller theory*, Moscow: GTTI, 1950.

[17] HEIER, S., *Grid integration of wind energy: onshore and offshore conversion systems*, 3rd ed., Chichester: John Wiley & Sons Ltd, 2014.

[18] ACKERMANN, T., *Wind Power in Power Systems*, 1st ed., Chichester: John Wiley & Sons Ltd, 2005.

[19] LEE, D., VAN, T.L., NGUYEN, T.H., "Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems", *IEEE Transactions on Energy Conversion*, 2015, vol. 30, no. 2, pp. 578–587, ISSN 1558-0059.

[20] MERABET, A., THONGAM, J., GU, J., "Torque and Pitch Angle Control for Variable Speed Wind Turbines in All Operating Regimes", in: Proceedings of 10th International Conference on Environment and Electrical Engineering (EEEIC), Rome, 8-11 May 2011, pp. 1–5.

[21] MUNTEANU, I., BRATCU, A.I., CUTULULIS, N.-A., CEANGA, E., *Optimal control of wind energy systems – Towards a global approach*, 1st ed., London: Springer, 2007.

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